Progress of the REMANTA project on MAV with flapping wings and of the International Universities mini UAV Competition

Agnès Luc-Bouhali[1] and Philippe Choy[2]
Office National d'Études et de Recherches Aérospatiales (ONERA)
Centre de Palaiseau, Chemin de la Hunière, 91761 Palaiseau Cedex, France

SUMMARY

This paper deals with the activities performed at ONERA concerning micro and mini aerial vehicles.

Since 2002 an internal project (REMANTA for REsearch programme on Microvehicle And New Technologies Application) has been carried out in order to improve our knowledge on science fields required for realizing a Flapping Wings Micro Air Vehicle.
This concept, the most innovative one, needs to merge different skills to develop new control and actuator concepts for building an agile MAV able to hover and cruise.
The three research topics are the following one:

- Flight dynamics and control
- Low Reynolds number aerodynamics
- Light materials, structures and actuators

In order to be able to provide the flight dynamic model with aerodynamic coefficients, hydrodynamic experiments have been realized for one single wing with 2D and 3D movements. The present Reynolds number range is typically 10^4-10^5, representative of cruise flight. Unsteady aerodynamic forces have been measured, vortex visualisations are also in progress for further understanding.
A description of the status of this research project will be given and future works presented.

Another activity is the organization of an International UAV Competition, opened to engineering schools and universities offering second cycle degree programmes (or equivalent for overseas). This competition is subsidized by the DGA (the French Arms Procurement Agency, of the Ministry of Defence).
The purpose of this competition is to demonstrate the technical feasibility and operational interest presented by mini UAVs (defined for this competition as a flying device not exceeding 70 cm in any of its dimensions) for use as a support for infantry troops evolving in hostile territory. The intended aid function is of a non-aggressive nature: its purpose is to provide an extension to the natural field of vision of the infantry soldier.
The competition, consisting in a simulation of operational scenarios on which will be in confrontation the different teams, will take place in May, 2005, in France. The application deadline is at the end of 2004.
A description of the competition and its rules will be done, as well as a brief presentation of the presently registered candidates' projects.

REMANTA PROJECT

INTRODUCTION

Mini or Micro Unmanned Aerial Vehicles (MAV) are today the focus of great interest.
Numerous Mini UAV demonstrators (fixed wing aircraft with wingspan greater than 20 or 30cm) have been studied and built. Due to the low mass and reduced payload, and low Reynolds number aerodynamics, this type of MAV is not easy to build but some recent realizations show it can be done [1, 2].

Flapping-wing MAVs could exhibit more flight agility than fixed-wing MAVs, but their conception is of greater challenge because of many entangled and intricate problems: mechanical design, efficient

[1] agnes.luc-bouhali@onera.fr
[2] philippe.choy@onera.fr

actuation, power system and control. Different ways may be chosen in order to study or build such MAV. Who doesn't know the Microbat [3] or the MFI from Berkeley [4] ? People may also decide to study fundamental problems like building smart flapping wings and developing knowledge for control and navigation of such flexible wings [5, 6, 7].

Such a complex problem including research on different topics was also chosen by ONERA in order to federate various research teams round a research project (in French "Projet de Recherche Fédérateur"). This project, named REMANTA (for REsearch program on Microvehicle And New Technologies Application) is devoted to flapping-wing MAV concept.
The aim is not to build or design a MAV demonstrator, but to improve the scientific and technical knowledge required to designing such a vehicle capable of hovering and cruising flights. Nevertheless, the μvehicle (total wing span less than 15 to 20 cm) we have in mind should hover and fly at a maximum speed of 10 m/s, with a total mass of 50 to 100g, with a maximal flapping frequency of about 30 to 40 Hz. With such dimensions, the Reynolds number (based on the chord length) is about a few 10^5 during cruising flight and 10^4 during hovering.

In 2002, ONERA decided to focus research during 4 years on three research topics:

- Flight dynamics and control
- Low Reynolds number aerodynamics
- Light materials, structures and actuators

The other important topics, such as on-board energy, sensors and on-board computer, data link, task distribution, are studied either in other projects [8, 9] or through collaborations [10].

Before presenting the status of each topic, we will firstly recall some information that can be found in the open literature concerning the flapping wing propulsion.

FLAPPING WING PROPULSION

We focused our search on animals able to hover and cruise.

The only bird which is able to hover is the hummingbird. Although it is a bird, the morphology of its wings involves a mode of operation very similar to an insect's one. The wing motion is determined entirely from the shoulder joint (elbow and wrist joints are fused) and the wing beat kinematics of the upstroke and downstroke are very similar. During stationary flight, the stroke plane is horizontal; the flap angle (stroke amplitude) varies from -60° to +60°, the rotation angle of the wing is ±45°and the frequency is approximately 25 Hz [11]. This kind of flight is extremely power-consuming. The hummingbirds may also cruise with considerable efficiency. In this case the stroke angle is vertical like other birds.
The hummingbirds are at the frontier between birds and insects

Most of insects may hover [12]. They may have two or four wings that operate independently or not. Their wings, when they are unfoldable, are passive structures without muscles: they are not actively controlled [13]. The movement is generated at the wing root by direct and/or indirect muscles that control wing beat, rotation and torsion. The required power is limited due to the use of the resonance phenomenon in the thorax (for very high frequencies). The kinematics can be described in the following figures. Generally, the stroke angle and the beat frequency are nearly constant in time.

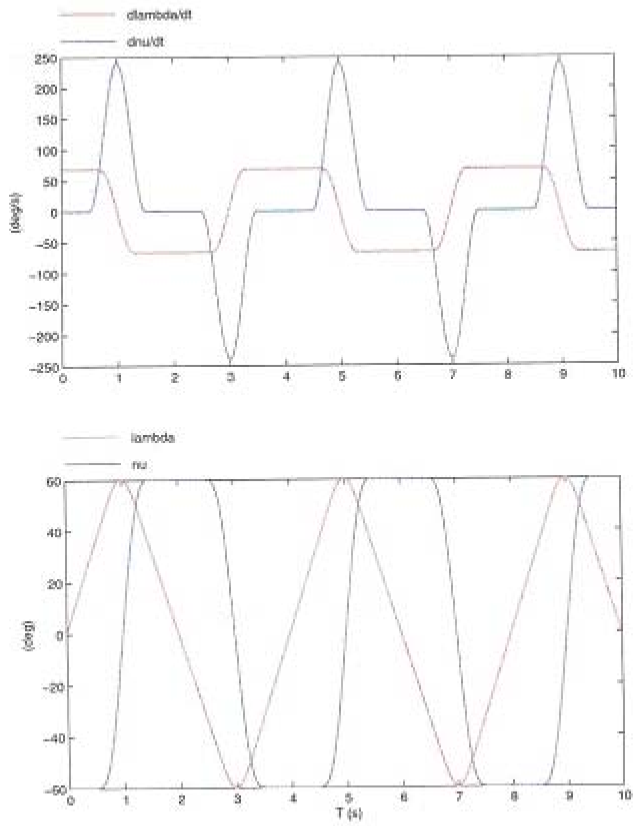

Figure 1 – a) Flapping speed and wing rotation speed during the beat cycle
b) Flap angle and wing rotation during a beat cycle

Each insect is then characterized by its particular kinematics, beat frequency and stroke angle, that can be linked together (see Figure 2, and Figure 3).

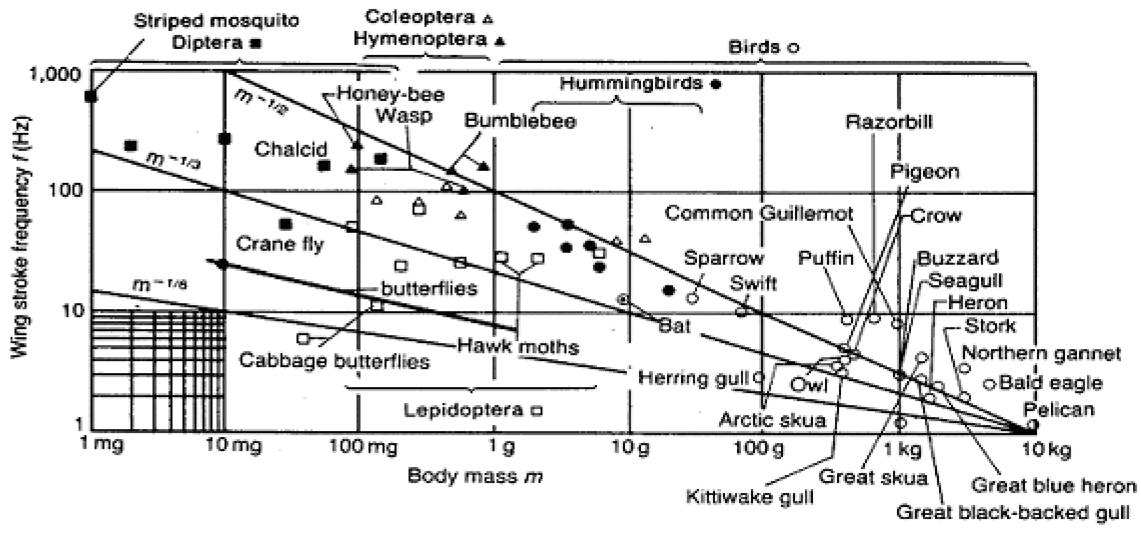

Figure 2 – Biological experimental results

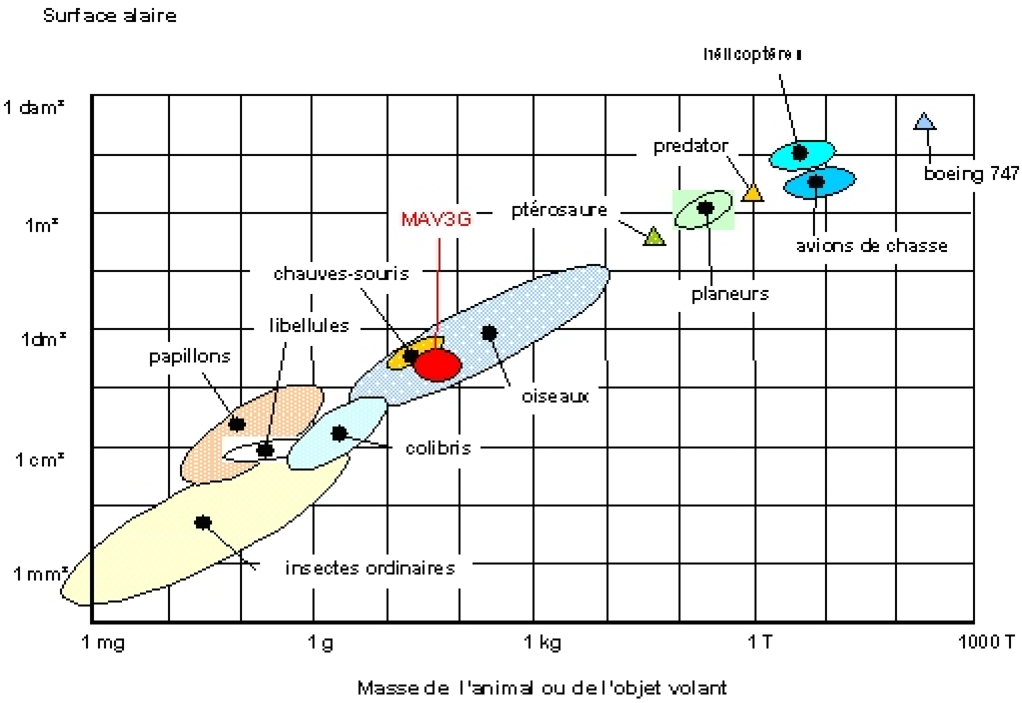

Figure 3 – Wing area versus mass for different flying vehicles

Today, the insect with the largest wingspan is a butterfly, the white witch moth (36 cm); the largest existing species of Odonata, Megalopropus caeruleata, a damselfly of Central South America, has a wingspan up to 19.1 cm and a body length of 12 cm. However, during the late Palaeozoic (about 300 million years ago) giant animals have existed like Protodonata with a wingspan as great as 70 cm, but a mass of about 20 g (see Figure 4) [14]. This fact may be correlated temporally with geological periods of increased oxygen concentration and atmospheric density [15]. This information shows that aerodynamics laws don't prevent MAV from existing with such a size.

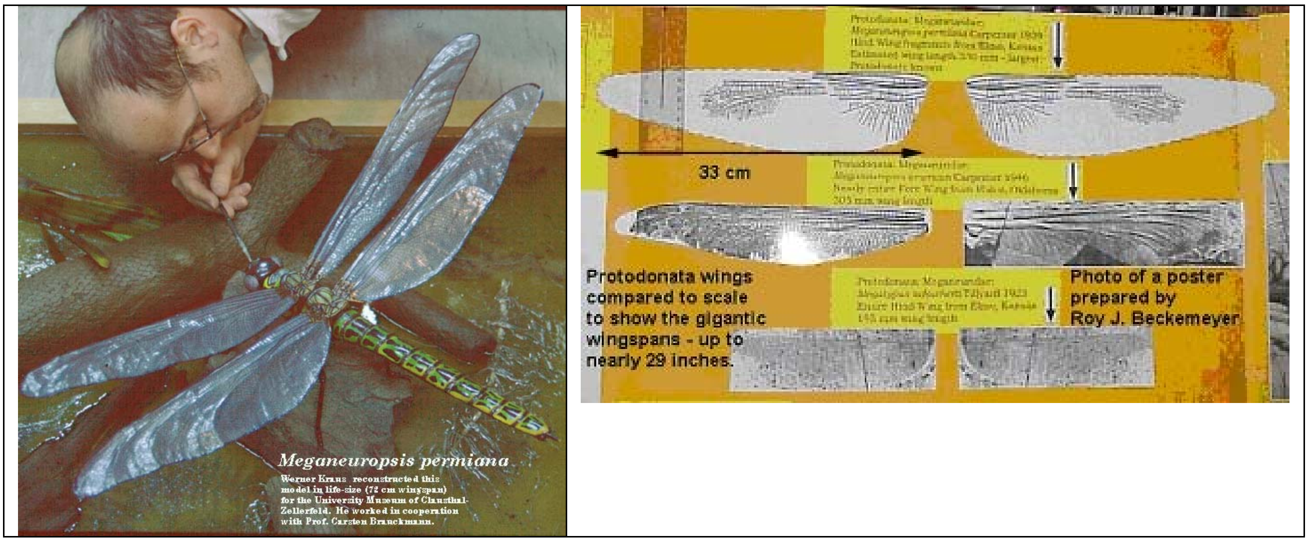

Figure 4 - Giant protodonata

All these considerations have suggested that flexible insect-like wings may be simpler to realize, easier to move without active control system and certainly less power consuming than articulated bird-like wings, even if the actuator system is not yet well-defined. The major difficulty will be to find kinematics effective for both hovering and cruising, with the same actuator system at the wing root and also to determine the control laws and the associated parameters.

TOPIC #1 : FLIGHT MECHANICS AND CONTROL

Our purpose is then to build a numerical flight mechanics model that can be used in order to test and then to choose control strategies.
As we are interested not only in cruise flight but also in stationary flight, we used an object approach for the common platform [16]: an exact mathematical formulation (with 6 dof) describes the kinematics of the articulated body (fuselage and two independent wings). The wing mass is neglected compared to the body mass: the mass centre is the central body one. The movements are calculated in a frame linked to the UAV, 4 angles being used for describing the wing movement (kinematics), the type of which can be very simply identified by:

- ξ, is constant during a beat cycle and characterizes the stroke plane
- λ, ν, μ vary during the beat cycle: λ defines the instantaneous stroke angle (flapping angle), ν is the rotation angle of the wing around its longitudinal axis (feathering angle) and μ represents the eventual lagging of the wing. For example, with ξ= 0°, the stroke plane is vertical and with ξ= 90° it is horizontal.

Aerodynamic forces are modelled using blade element theory. Although this 2-D approach does not represent span-wise flow observed on insect wing [17], it gives a good agreement between actual force measurements and model, which is also readily applicable to control design [18].
According to 2D approach, the wing is divided in slices, the local elementary forces are then summed along the wing span giving the global force and momentum: mean thrust and lift are calculated, enabling the evaluation of tested kinematics efficiency (see Figure 5).

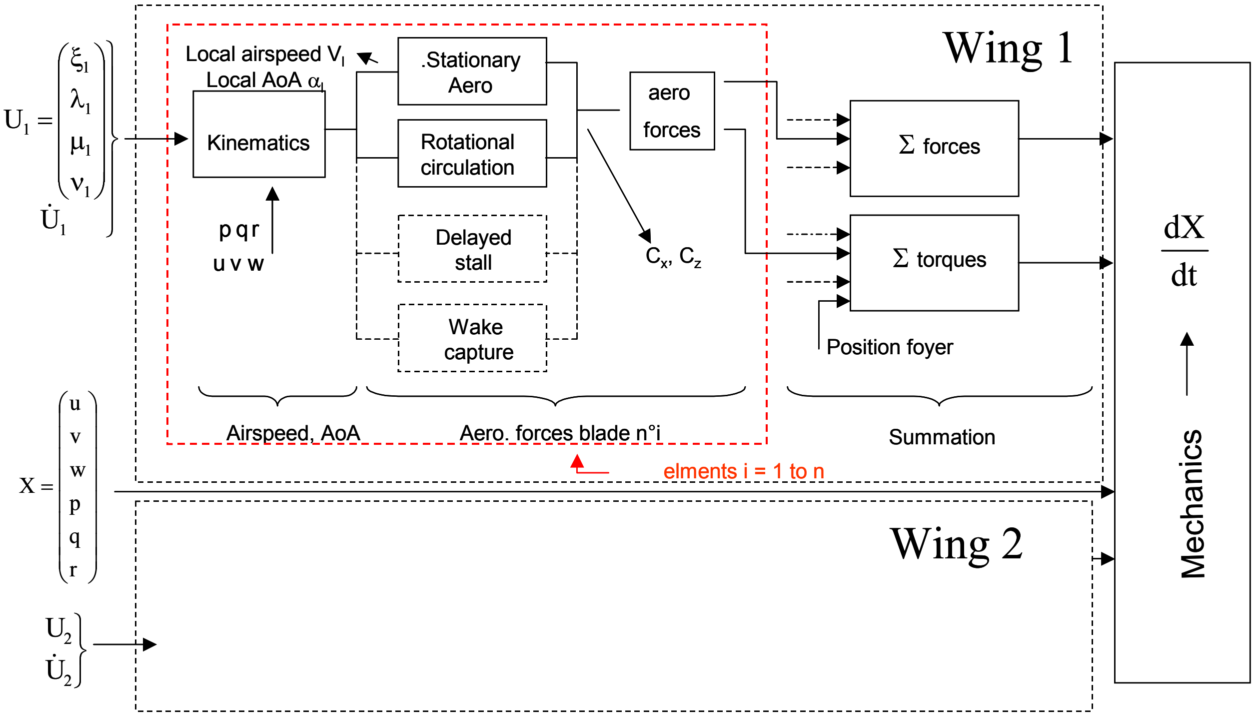

Figure 5 - Structure of the flight mechanics model

The major difficulty is to have aerodynamic models well-adapted to the phenomena encountered around such vehicle. It is well-known that flapping wing aerodynamics is not well known! Due to low Reynolds number regime, stationary aerodynamics is not always sufficient to explain insect or bird flight. Lot of research has been done and is currently done in order to understand and quantify the phenomena.

The *Robofly* experiment [19] is the main information source and concerns a Reynolds number range of around a few hundreds. That is lower than the expected one for our application. Otherwise, kinematics for cruise or hovering flights are very different, either concerning the beat frequencies or variation speeds, or concerning the angle amplitudes. These important limitations have led us to define an aerodynamic task in the REMANTA project that is described in the next chapter.

Nevertheless, different existing unsteady models have been chosen and implemented, such as rotational circulation and added mass, to create a complete simulation model that has been compared to the results obtained by Dickinson.

Simplified longitudinal model has also been written in order to do system analysis and control. First of all influence of the phase between the rotation and the flapping of the wing has been studied, together with the time history of the wing rotation angle.

TOPIC #2 : EXPERIMENTAL AERODYNAMICS

Considering the need of aerodynamic data for the flight mechanics models, in a domain of low Reynolds [20] number not well-documented (10^4-10^5], we decided to follow an experimental way. The gathering of instantaneous data (Cx, Cz, Cm, …) will permit us to have an experimental data base. These data should also later help for code validation.

Unlike conventional aircrafts which are usually too large to be tested at scale 1 in ground facilities, mini or micro UAV are sufficiently small to be tested at actual size. On the contrary, the size of the model might have to be increased due to realization costs or instrumentation difficulties. Similitude rules have to be respected if we want to have correct measurements: not only the Reynolds number but also the Strouhal number (or the reduced frequency) must be identical between flight and test conditions. The kinematics must also be the same.
As we wanted to measure torques and forces, we have chosen to use water tank or tunnel as test facilities: inertial forces will be then much lower than aero or hydrodynamic forces.

Two existing facilities are involved in the project: the water tank in ONERA/Lille (see Figure 6) and the water tunnel in ONERA/Toulouse (see Figure 6). In the water tank, a 5 components balance has been specially developed for the REMANTA project. In the water tunnel, visualisations with laser tomography and image acquisitions are foreseen.

Figure 6 - Test facilities involved in the REMANTA project

A mechanism has been studied and built (see Figure 7); it can move one rigid wing with 2D (plunging and pitching) or 3D (flapping and pitching) kinematics; the stroke plane is vertical: this device allows us to reproduce bird-like kinematics, with moderate stroke and incidence amplitudes. However, since only one motor is used for generating the kinematics, flapping and pitching are linked together. The airfoil of the wing is a NACA 0012: its thickness is sufficient to accept the balance inside the structure, and the model is well documented for both steady and unsteady aerodynamics.
This experiment is the first step made in order to understand flapping wing aerodynamics and to check that the way we chose is the good one.

A first test campaign has been made at the end of year 2003 with more than 400 tests; the analysis of all these data is still in progress [21]. For 2D tests, the reduced frequencies and the Reynolds numbers (based on the chord length and calculated with the relative speed) are respectively in the range [0.04-0.25] and [10^4-10^5].

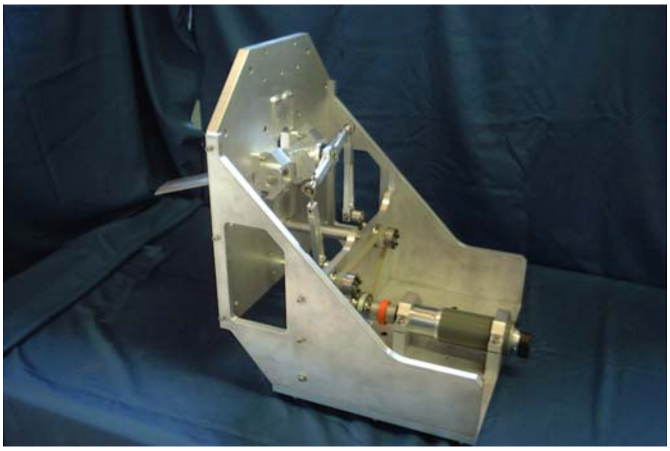

Figure 7 - Coupled mechanism

The aerodynamic laws derived from these experimental data through identification process will feed the flight mechanics models but also provide specifications for actuators (see next chapter).

TOPIC #3 : MATERIALS, STRUCTURES AND ACTUATORS

The aim is to evaluate a concept of wing actuation based on resonant thorax type, inspired by insects, and concepts for passively twisting wings

The resonant thorax shows a priori interesting energetic characteristics (minimal dissipation) and should make it possible to use actuators having coupling coefficients close to 1. On the one hand, the objective is to make sure that the "thorax" will have the required kinematics performances, on the other hand, that the wing shape deformations remain controlled under “passive control”.

Concerning the thorax, we are using intermediate model (with masses, springs and equivalent rigid elements) to predimension dynamic sub-structuring, but realization of prototypes is essential to check the suggested concepts. Nevertheless, the kinematics has to be designed in order to precisely know the different parameters defining the concept: beat frequencies, angle amplitudes, wished displacements, applied forces. Current works are in open loop: kinematics obtained from flight mechanics studies or found in the literature give us some orientations, but later a closed-loop approach will be necessary.

Concerning the wings, examination of insect wings has suggested a fabrication of a wire-mesh surrounded by a thin membrane. This wire-mesh processed by composite prepregs made of carbon fiber and epoxy resin offers an attractive solution (see Figure 8). Flexibility may be adjusted by increasing/decreasing of the number of carbon tows. A thermoplastic polyester film pasted on the wire-mesh constitutes an interesting envelope to achieve this wing fabrication. Tested by dynamic flexural, this realization is quite suitable to meet the expected mechanical requirements from a MAV wing.

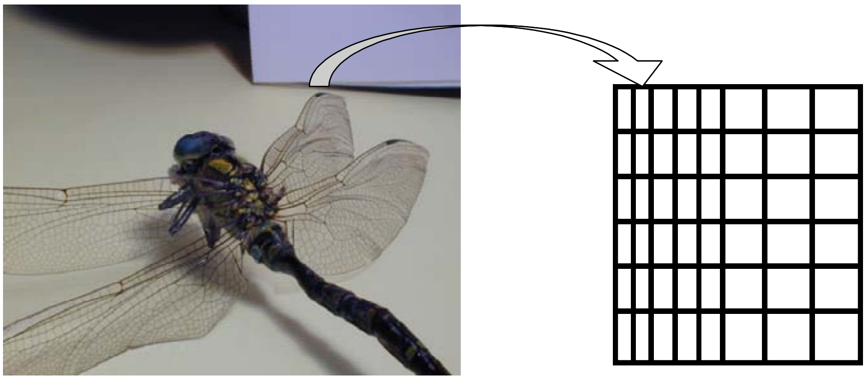

Figure 8 - Wing concept

The remaining question to be solved is: how to verify that the wing shape deformation is the best, for the best effective kinematics ?
Indeed, aeroelastic calculations have shown that the wing flexibility has an huge effect on the aerodynamic performance, even if aerodynamic models are approximate (i.e. using classical dynamic stall models that do not correctly represent low Reynolds unsteady aerodynamics): the results of the beat cycle optimisation made for a rigid wing is definitely not applicable to a flexible wing.

Tests at scale 1, with the final wing structure, seem to be essential. A specific instrumentation will be also required to determine the actual performance. The acquired experience will be very useful for the in-flight control of the future µMAV.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The work completed up to now has allowed to develop a flight mechanics model which has been partly verified and optimisation studies have begun. Concerning unsteady aerodynamic models for low Reynolds number, experiments with a coupled mechanism are in progress in order to build a data base. These data don't currently cover all the domain we want to prospect, particularly the kinematics specific to the hovering flight. This is why a new mechanism is being defined with independent actuation for stroke and wing rotation angles. This testbed will also be used with thin airfoil and even flexible wings in order to open the research towards aeroelasticity problems.
In addition, first achievements of composite wings have been made, as well as an initial concept of a resonant thorax, more complete integration being needed before building demonstrators.

After 2.5 years, the REMANTA project has contributed to gather different competences and form a multidisciplinary team which should be an active asset for further practical developments or international cooperations.

INTERNATIONAL UNIVERSITIES MINI UAV COMPETITION

Another activity of ONERA in the field of mini UAVs is the organisation of the International Universities Mini UAVs Competition. This competition, subsidized by the DGA (the French Arms Procurement Agency, of the Ministry of Defence), is opened to engineering schools and universities, and is scheduled for May, 2005.

The purpose of this competition is to demonstrate the technical feasibility and operational interest presented by mini UAVs for use as an aid infantry troops located in hostile territory. The intended support function is of a non-aggressive nature: its purpose is to provide an extension to the soldier's natural field of vision. The competitors must develop and present a complete system, including a flying observation system (the UAV) equipped with at least one video camera, and a ground station. The final phase of the competition will take place in an artificial combat village in France. Here, competitors will be required to simulate an operational scenario.

We are eager to have a follow-up to this competition. It has still to be decided if it should be annual or bi-annual, and we do not exclude the possibility of extending the organization to European partners.
21 teams (French or French associated with other countries) are registered today. The closing date for application is December 31, 2004. Complete regulation and application forms may be downloaded from the competition web-site: http://concours-drones.onera.fr

The DGA will provide a €15,000 1st prize, and additional prizes will be announced on the competition web-site before the closing date for registration. The jury will award competitors who have successfully passed the different tests. Any remaining prize funds will be devoted to future competitions.

The scenario of the final test is described in the Appendix I of the competition rules; it is based on a situation designed to simulate an infantryman or specialized unit moving through a hostile urban area. The unit is exposed to hidden snipers and risks of attack by hostile forces. Barricades and rubble prevent the use of vehicles. The UAV(s) deployed by this small unit must help to determine the best of several possible ways forward, by detecting and transmitting details of the location of barricades and identifying zones exposed to direct snipers' fire. In addition, it must provide a stabilized video image for each target.

The system must be more sophisticated than a simple R/C model, and in particular it has to pass a safety exam before being authorized to fly. Indeed, the jury will give points for ambitious criteria such as : the functional independence of the system, the simplicity of setting-up and piloting by an unspecialized operator, the capacity of hovering and evolution in urban environment, the capacity to provide the operator with data from outside its field of vision, the miniaturization of the vehicle, the technological innovation, the endurance (flying time)...

The competences used will be highly multidisciplinary and will include aerodynamics and flight dynamics, micro-technologies, data processing / automatics, energetics (motorization, electric source of energy), datalinks, possibly artificial intelligence, etc...

REFERENCES

[1] J. M.Grasmeyer, M.T.Keennon, Development of the Black Widow Micro Air Vehicle, AIAAPaper-2001-0127

[2] T.Kordes, M.Buschmann, P.Vörsmann, Behavior of a Micro-Aerial-Vehicle (Mav) in an Environment of a Turbulent Atmosphere, ICAS 2002 Congress

[3] T.N.Pornsin-Sirirak, T.N.Tai, C.M.Ho, M.Keennon., Microbat: a Palm-Sized Electrically Powered Ornithopter, Caltech Pasadena, University of California and AeroVironment Inc.

[4] L.Schenato, X.Deng, W.Wu, S.Sastry, Virtual Insect Flight Simulator (VIFS) : a Software testbed for Insect Flight, Departement of Electrical Engineering and Computer Sciences, University of California of Berkeley

[5] R.Zbikowski, Flapping Wing Autonomous Micro Air Vehicles: Research Programme Outline, 14th International Conference UAVS, 12-14 April 1999, Bristol, UK

[6] M.Lasek, J.Pietrucha, K.Sibilski, Micro Air Vehicle Maneuvers as a Control Problem of Flexible Flapping Wings, AIAA Paper 2002-0526, 40th AIAA Aerospace Sciences Meeting & Exhibit, 14-17 January 2002, Reno NV

[7]D.LRaney., E.C.Slominski., Mechanization and Control Concepts for Biologically Inspired Micro Aerila Vehicles, AIAA 2003-5345, AIAA Guidance, Navigation & Control Conference, 11-14 August 2003, Austin, Texas.

[8] P.Fabiani, PRF RESSAC : Recherche et Sauvetage par Système Autonome Coopérant au sein d'un réseau d'information et de décision – Rapport de Synthèse, ONERA RT 7/06752 DCSD, Janvier 2004

[9] O.Dessornes, C.Dumand, D.Gaffié, J. Guidez, Y. Ribaud, Micro Combustion Chambers Principles Dedicated To Microturbines, POWERMEMS2003, Makuhari, Japan dec.4-5, 2003

[10] T.Keuter, D.Hermans ,G.Boyet, Aerodynamic Research On Lifting Surfaces For Micro & Mini Uavs, UAVS, 8-10 April 2002, Bristol (UK).

[11] D.L.Altshuler, R.Dudley, Kinematics of hovering hummingbird flight along simulated and natural elevational gradients, The Journal Of Experimental Biology 206, 3139-3147 (2003)

[12] A.K.Brodsky, The evolution of Insect Flight, Ocford Science Publication, 1994

[13] S.A.Combes, T.L.Daniel, Flexural stiffness in insect wings I. Scaling on the influence of wing venation, The Journal Of Experimental Biology 206, 2979–2987 (2003)

[14] W.Kraus RWTH Aachen, Germany, and Web Page http://www.windsofkansas.com by Roy J.Beckemeyer

[15] R.Dudley, Atmospheric Oxygen, Giant Palaeozoic Insects and the Evolution of Aerial Locomotor Performance, The Journal of Experimental Biology 201, 1043–1050 (1998)

[16] T.Rakotomamonjy, T.Le Moing, M.Ouladsine, Simulation of a flapping-wing Micro Air Vehicle, EMAV 2004, Braunschweig

[17]C. P.Ellington, C.Van den Berg, A. P. Willmott, A. L. R. Thomas, Leading-edge vortices in insect flight, Nature 384, 626-630 (1996)

[18] S.P.Sane and M.H.Dickinson The aerodynamic effects of wing rotation and a revised quasi-steady model of flapping flight, The journal of Experimental Biology 205, 1087-1096 (2002)

[19] M.H.Dickinson, F.O.Lehmann, S.P.Sane, Wing rotation and the aerodynamic basis of insect flight, Science, 284:1954-1960, June 1999

[20] Low Reynolds Number Aerodynamics on Aircraft including applications in Emerging UAV Technology, RTO-AVT-VKI lecture Series 2004, November 24-28, 2003

[21] J.B.Paquet, Characterization of Flapping Wings in Water Tank for µUAV, EMAV 2004, Braunschweig